and two of the paper divisions along the axis of X go to one second, whilst five units of retinal excitement, or apparent brightness, go to every degree along the axis of Y. It is therefore evident that, if the curve is to represent the actual rate of rise and fall of retinal excitation when one looks at a white surface of the albedo stated, and which is afterwards made to disappear, the time scale must be different from that just mentioned. From rather rough experiments made with a photographic shutter by the writer, it would appear that the whole of the rise from 0° to 360° takes about half a second: if this be true, and the assumption mentioned above (in *italics*) be correct, we must consider each of the paper divisions, of which every other one is marked in black along the axis of X, to represent one twentieth part of one second. The data for the construction of the curve are given in the foregoing table.

The Nature of the γ-Rays excited by β-Rays.

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In a previous paper,[*] it was shown that the β-rays of radium E excited γ-rays[†] in different materials, the amount increasing with the atomic weight of the substance used. It was found that the γ-radiation was largely increased when the β-rays fell on a lead screen suitably placed, and as the active material, radium (D + E + F), was mixed with lead sulphate confined in a small space, it was obvious that some, if not all, of the γ-radiation issuing from the mixture was due to γ-rays excited by β-rays in the lead impurity. It thus seemed possible that no primary γ-rays were emitted by radium E.

By using a more suitable source, in which the active material was spread in a thin layer over filter paper, it has been found that a primary γ-radiation is emitted from the active matter. This radiation, however, is much softer than that excited by the β-rays in lead. A more detailed account of these primary rays will be given later.

The main object of the present investigation was to examine carefully the question whether the γ-ray excited by a β-ray travels in the direction of the

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[*] Gray, 'Roy. Soc. Proc.,' 1911, A, vol. 85, p. 131.

[†] In the paper mentioned, the term secondary γ-rays was given to γ-rays excited by β-rays. To distinguish, however, from another phenomenon, described later, the term "excited" γ-rays is now used.

β-ray. This point is of considerable theoretical importance as it throws light on the question whether the γ-ray is a spreading pulse or corpuscular in nature. The experiments and their discussion may be conveniently divided into two parts:—

(1) A determination of the relative values of the emergent and incident γ-rays (using the usual convention) excited by the β-rays in plates of different thicknesses and different materials.

(2) An attempt to explain the results on the assumptions that the γ-ray is corpuscular in nature and that it moves in the direction of the β-ray exciting it.

Secondary γ-Rays.

Before describing the results in detail it is desirable to draw attention to an interesting effect observed when the primary γ-rays of radium E fall on elements of low atomic weight such as carbon.

The effect is shown by the following experiment. The active material A (fig. 1) was placed between two plates of graphite, of thickness sufficient to absorb all the β-rays, and introduced under the electroscope E (the bottom of which was closed by aluminium 1 mm. thick). Readings were taken with and without different radiators R under the active material. The results are given in Table I in terms of divisions per minute of the electroscope.

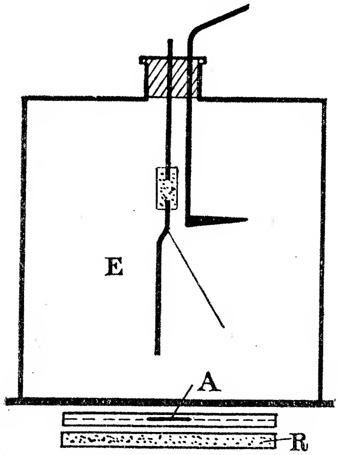

Fig. 1.

From the following table it is seen that the increase in the reading is very marked when radiators of low atomic weight are used. If the penetrating γ-rays of radium had been used as a source of radiation, the

Table I.

Radiator.	Divisions per minute.	Percentage increase.
No radiator	12·50	
Graphite ...... 4·98 mm. thick	13·50	8
„ ...... 12·40 „	14·40	15
„ ...... 18·40 „	15·25	22
„ ...... 40·00 „	15·70	25
Aluminium ... 2 „	13·10	4·80
Sulphur ...... 10 „	13·10	4·80
Iron .... 2 „	12·55	0·05
Lead .... 2 „	12·55	0·05

increase of the reading would only have been of the order of 1 per cent., so the effect observed is not likely to be one of ordinary scattering.

A provisional explanation is that characteristic radiations are emitted by the elements of low atomic weight, but more experiments are necessary before this can be definitely established. For the sake of distinction we say that primary γ-rays produce secondary γ-rays in elements of low atomic weight.

Experimental Arrangements and Results.

Some experiments will now be considered which tested whether there was any definite relation between the direction of the β and excited γ-rays. The experimental method was as follows (see fig. 2):—E was an electroscope 17 cm. cube, the bottom of it consisting of aluminium 1 mm. thick, the rest of iron 1 mm. thick. This was placed on a piece of wood W, above the poles N, S, of a powerful electromagnet. The wood was 8 mm. thick and in it was placed a piece of lead P to diminish the direct effect of γ-rays from active material placed at A. The pole pieces were covered with graphite 1·8 mm. thick. Below A′ was a piece of wood 3 mm. thick. Graphite and wood were so used, owing to the facts that comparatively few γ-rays are excited in them, and few β-rays reflected from them. LM represents the plate or "radiator" experimented on, and this was placed midway between A and A′, so that,

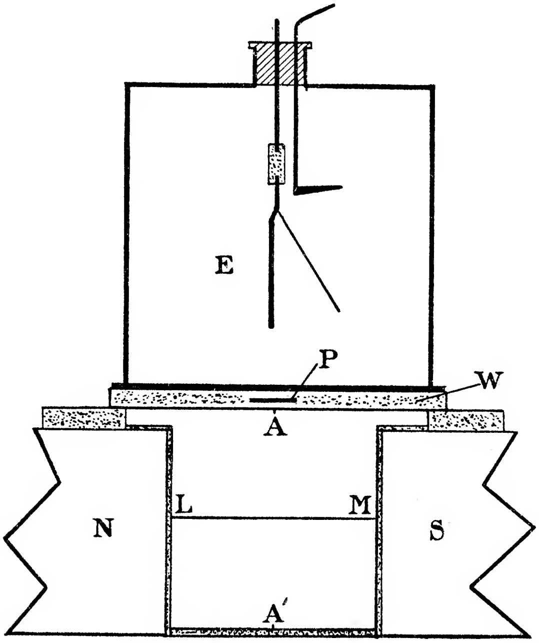

Fig. 2.

whether the active material was placed at A or A′, the intensity of β-rays striking LM was the same in either case. The dimensions of the apparatus were AA′ = 12·6 cm.; LM = 11 cm. (length at right angles to LM = 20 cm.); length of pole pieces 14 cm.

To measure emergent γ-rays, the active material was placed at A′, and readings were taken without and with a magnetic field strong enough to turn the β-rays away from the plate LM, the difference being called E′. The strength of the magnetic field used was 1100 Gauss.

To measure incident γ-rays, the active material was placed at A, and readings were taken with and without the plate LM, the difference being called I′. E′ and I′, the numbers obtained in this way, do not give us the true emergent and incident radiation, but have to be corrected for certain disturbing effects. The uncorrected values, E′ and I′, for the different radiators used are given below.

Table II.

Radiator LM.	Emergent γ-rays (uncorrected).	Incident γ-rays (uncorrected).	E′/I′.
1 lead foil	1·33	0·60	2·22
2 lead foils	1·73	1·05	1·65
3 „	2·04	1·50	1·36
4 „	2·24	1·75	1·28
5 „	2·25	1·93	1·16
6 „	2·22	2·05	1·08
7 „	2·18	2·16	1·01
9 „	2·00	2·20	0·91
Iron, 0·4 mm. thick	1·15	0·64	1·80
Paper	0·56	0·10	5·60

The mass per unit area of 1 lead foil is 0·0173 grm.

The numbers are expressed in divisions per minute of the electroscope. The larger numbers have a probable accuracy of about 2 per cent. Examples of the readings obtained are given below:—

Incident γ-rays.		No radiator	5·00
		5 lead foils	6·93
Emergent γ-rays.			
	No radiator at LM.	No field	6·50
		Magnetic field	5·90
	Radiator, 4 lead foils.	No field.........................	5·00
		Magnetic field................	2·76
	Radiator, iron plate.	No field	4·05
		Magnetic field................	2·90
	Radiator, 7 lead foils.	No field	3·98
		Magnetic field................	1·80

Taking the case of paper, iron and six lead foils it will be seen that the ratio of emergent to incident γ-rays is greater the lower the atomic weight. Now, in the plate LM, β-rays are scattered and some are sent back on their path. The paper reflects 8 per cent., the iron 40 per cent. and the lead foils about 70 per cent. of the β-rays falling on them,* so that in the lead many more rays in comparison are travelling in a direction opposite to their original direction. If we assume that the γ-ray moves in the direction of the β-ray exciting it, we should expect approximately the following ratios for emergent to incident γ-rays:—

Paper, 100/8, Iron, 100/40, Lead, 100/70.

The uncorrected ratios found show this order of magnitude. We can, therefore, draw the conclusion that most of the energy of the γ-ray excited by a β-ray moves in the direction of the β-ray.

To proceed further, it is necessary to make the corrections referred to above. They are few in number, and reasonably definite.

Possible disturbing effects are:—

(1) The magnetic field may affect the reading. That the magnetic field itself has no effect on the reading was shown by putting the active material below the electroscope and covering it with enough graphite to cut off β-rays. There was then no difference in the electroscope reading whether the magnetic field was applied or not.

(2) β-rays from the screen LM, which strike the bottom of the electroscope, may excite γ-rays and so increase our measure of γ-rays. This was corrected for as follows:—The active material was placed at A′ and readings were taken with and without a magnetic field, there being no radiator at LM. The difference (w) gives the production of γ-rays (as measured by the electroscope) in the material above the plane LM. When measuring emergent γ-rays the correction applied was $w \times t$, where t is the fraction of β-rays transmitted by the plate LM. When measuring incident γ-rays the correction applied was $w \times \rho \times f$, where ρ is the fraction of β-rays reflected by the plate; f is a factor introduced because of the fact that reflected β-rays are relatively slower. In the present case

$$w = 0{\cdot}60.$$
$$f \text{ (see p. 523)} = 0{\cdot}78.$$

(3) When the active material is placed at A, γ-rays (excited and secondary) are formed in the material below LM. When the radiator LM is in position,

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* Throughout, by percentage or intensity of β-rays, is meant percentage or amount of ionisation caused by the β-rays. By strength of γ-radiation is meant the ionisation caused by that radiation in the electroscope E.

some of these γ-rays are not produced, causing the measure of incident γ-rays to be too low. The correction was found as follows:—A piece of graphite, 12·41 mm. thick, placed above A′, increased the reading by 0·20 division per minute. An experiment similar to those on secondary γ-rays showed that the effect of the γ-rays formed in the material below LM when the radiator was not in position was about one-third of this, or 0·07. To the measure of incident γ-rays a number less than 0·07 was consequently added.

The experiment on secondary γ-rays shows that there is no correction for the formation of secondary γ-rays in the iron and lead plates.

Corrections (2) and (3) are the only ones that have to be considered. We, therefore, get our true emergent and incident γ-rays (E and I, say) from the equations

$$E = E' - 0{\cdot}60 \times t,$$

$$I = I' - 0{\cdot}60 \times \rho \times f + m \times 0{\cdot}07,$$

m being $\not>$, though usually taken = unity.

The corrected values of E and I are given in Table III.

Table III.

Radiator LM.	t.	ρ.	Emergent γ-rays = E.	Incident = I.	E/I.
Paper	0·02	0·08	0·56	0·05 ?	
Iron	0	0·40	1·15	0·52	2·21
1 lead foil	0·46	0·49	1·05	0·40	2·62
2 lead foils	0·266	0·61	1·57	0·80	1·96
3 "	0·173	0·65	1·94	1·25	1·58
4 "	0·112	0·67	2·17	1·50	1·43
5 "	0·074	0·69	2·21	1·67	1·33
6 "	0·050	0·70	2·19	1·80	1·22
7 "	0·034	0·70	2·16	1·91	1·18
9 "	0·016	0·70	1·99	1·95	1·02

The results for lead are shown by the curves in fig. 3. In the case of paper there is very little incident radiation. The ratio E/I found for iron, 2·21, agrees well with the ratio expected, 2·50. In the case of lead, the numbers are larger and more accurate, and an explanation of the results has been obtained by our assumption that the γ-ray is corpuscular in nature, and moves in the direction of the β-ray exciting it.

Let us suppose that the plate ABB′A′ (fig. 4) represents the plate under examination, and XX′ the source of β-rays. Near any point P of the plate, β-rays will be moving in all directions. We call β-rays moving from below any plane CC′ to above it "forward" β-rays, and signify them by the letter R.

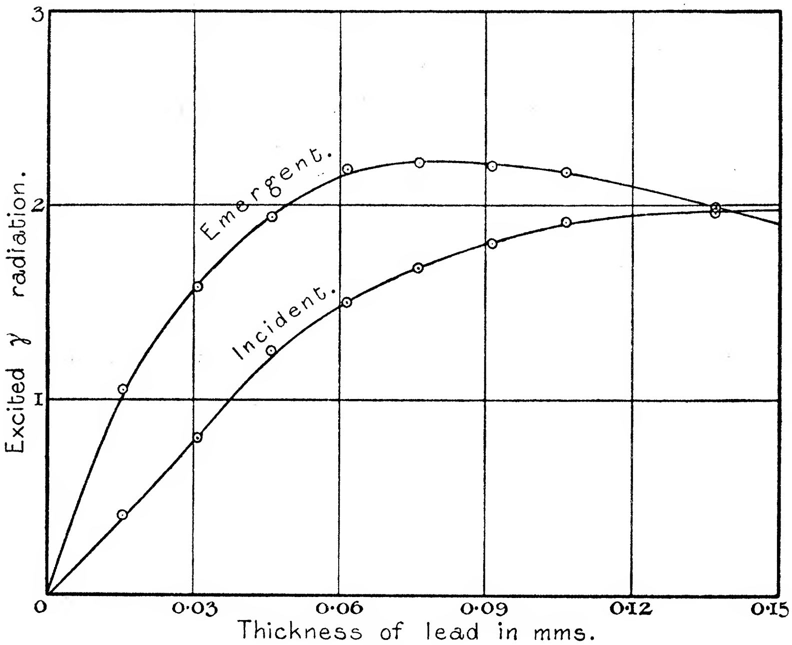

FIG. 3.

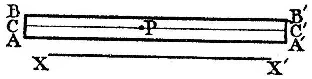

FIG. 4.

β-rays moving in opposite directions are called "backward" β-rays, and are signified by the letter r. If $AB = A'B' = d$, the thickness of the plate, $AC = x$, and the velocity distribution of forward rays is independent of x, the γ-rays formed by them will be proportional to $\int_0^d R\,dx$, etc. If the γ-ray moves in the same direction as the β-ray we must have

$$E = k\int_0^d Re^{-\lambda(d-x)}dx,$$

where λ represents the average absorption coefficient of the rays in the plate. Similarly we must have

$$I = k'\int_0^d re^{-\lambda' x}dx,$$

λ' representing the average absorption coefficient of γ-rays formed by the backward rays, and k'/k the relative efficiency of the backward β-rays in exciting γ-rays in "thin" sheets.*

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* Throughout, a "thin" sheet is taken as one so thin that practically no β-rays are reflected from it.

We have now to find how R and r vary with x and d. We will assume, for the moment, that the velocity distribution of both forward and backward rays is the same and independent of x and d. In a layer dx, forward β-rays lose a certain amount by absorption, and also by scattering, gaining a certain amount by the scattering of backward β-rays. We therefore write

$$\frac{d\mathrm{R}}{dx} = -\alpha\mathrm{R} - p\mathrm{R} + pr \tag{1}$$

$$-\frac{dr}{dx} = -\alpha r - pr + p\mathrm{R}, \tag{2}$$

$-\alpha\mathrm{R}dx$ representing the amount lost by the forward β-rays by absorption in the layer dx, $-p\mathrm{R}dx$ the amount lost by scattering of the forward rays, etc.* The solution of these equations is given by

$$\mathrm{R} = \frac{1}{1-\mathrm{P}^2e^{-2\mu d}}\{e^{-\mu x} - \mathrm{P}^2e^{-2\mu d}e^{\mu x}\}, \tag{3}$$

$$r = \frac{\mathrm{P}}{1-\mathrm{P}^2e^{-2\mu d}}\{e^{-\mu x} - e^{-2\mu d}e^{\mu x}\}. \tag{4}$$

The rays being supposed initially to be of unit intensity, equations (3) and (4) satisfy the boundary conditions

$$\mathrm{R} = 1, \quad x = 0; \quad r = 0, \quad x = d.$$

P and μ are connected with α and p by the equations

$$p = \frac{2\mu\mathrm{P}}{1-\mathrm{P}^2}, \qquad \alpha = \frac{\mu(1-\mathrm{P})}{\mu(1+\mathrm{P})}.$$

For the fractions transmitted and reflected we get

$$t = \mathrm{R}_{x=d} = \frac{1-\mathrm{P}^2}{1-\mathrm{P}^2e^{-2\mu d}}e^{-\mu d}, \tag{5}$$

$$\rho = r_{x=0} = \frac{\mathrm{P}}{1-\mathrm{P}^2e^{-2\mu d}}(1-e^{-2\mu d}). \tag{6}$$

μ is, therefore, the term ordinarily known as the absorption coefficient, and P the fraction of β-rays reflected from a thick plate. It is known that the backward rays are slower than forward rays, and so our equations can only be regarded as approximations. We can see, however, if, by choosing P and μ properly, not necessarily the same for both backward and forward rays, we can get equations (3), (4), (5) and (6) to fit experimental results.

We will apply the equations to the results for the different lead foils. It was found that μ was given by $e^{-\mu d_1} = 0{\cdot}68$ when d_1 = thickness of a single foil. A thick lead plate reflects 70 per cent. of the rays falling on it.

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* The assumptions made are the same as those used in a theory of the absorption of β-rays given by Schmidt, 'Ann. der Phys.,' 1907, A, vol. 23, p. 671.

Taking $e^{-\mu d_1} = 0{\cdot}68$, $P = 0{\cdot}70$, and substituting in equations (5) and (6) we get

$$t = 0{\cdot}447_1,\ 0{\cdot}263_2,\ 0{\cdot}169_3,\ 0{\cdot}111_4,\ 0{\cdot}0746_5,\ 0{\cdot}0508_6,\ 0{\cdot}0343_7,\ 0{\cdot}159_9,$$

$$\rho = 0{\cdot}483_1,\ 0{\cdot}611_2,\ 0{\cdot}662_3,\ 0{\cdot}68_4,\ 0{\cdot}693_5,\ 0{\cdot}70_6,\ 0{\cdot}70_7,\ 0{\cdot}70_9.$$

The experimental values are—

$$t = 0{\cdot}460_1,\ 0{\cdot}266_2,\ 0{\cdot}173_3,\ 0{\cdot}112_4,\ 0{\cdot}0740_5,\ 0{\cdot}0502_6,\ 0{\cdot}340_7,\ 0{\cdot}158_9,$$

$$\rho = 0{\cdot}490_1,\ 0{\cdot}610_2,\ 0{\cdot}655_3,\ 0{\cdot}0675_4,\ 0{\cdot}69_5,\ 0{\cdot}70_6,\ 0{\cdot}70_7,\ 0{\cdot}70_9.$$

The suffixes 1, 2, etc., refer to the number of lead foils.

Equations (5) and (6) with the values given to μ and P therefore fit experimental results very well. It follows that equations (3) and (4) must also hold approximately. This can be seen by trials similar to the following. Suppose the plate ABB′A′ consists of two lead foils, and we wish to find the intensity of R and r in the middle of these foils, d being the thickness of one foil. We have to find R and r, for $x = d_1$ and $d = 2d_1$.

Equation (3) gives $R = 0{\cdot}588$, but one lead foil reflects 49 per cent., therefore r should be

$$0{\cdot}588 \times 0{\cdot}49 = 0{\cdot}285;$$

equation (4) gives

$$r = 0{\cdot}282.$$

Equations (3) and (4) thus give, with reasonable accuracy, the intensity of R and r inside the lead plates.

The relative power of the backward β-rays in exciting γ-rays in thin sheets, or k'/k, was found in the following manner. The active material was placed at LM and readings were taken of the emergent radiation excited in a lead plate 0·1 mm. thick, placed just below A

(1) With nothing under the active material.
(2) With a lead plate under the active material.

In the second case the emergent γ-radiation is increased by the β-rays reflected from the lead under the active material.

The active material used was spread over filter paper about 8 sq. cm. in area and placed between two thin sheets of paper. When lead was placed under this and a magnetic field applied, the field directed some β-rays on to the lead and so excited γ-rays. For this reason, the emergent γ-radiation was measured by interchanging lead and cardboard radiators at A, first lead and then cardboard being underneath. The interchange made no difference to the intensity of γ-radiation from the active material as the cardboard absorbed so little of it. The difference of the readings was taken to be proportional to the emergent γ-radiation excited in the lead, as that excited in the cardboard was only about 8 per cent. of the difference. In this way it was found that for the same intensity of β-rays, reflected β-rays produced 0·76 of the emergent γ-radiation excited by direct rays in a lead plate 0·1 mm. thick.

The β-radiation was measured by placing the active material 10 cm. below a small electroscope. Using a bare preparation of radium E under the same conditions, a lead plate reflected apparently 73 per cent. of the β-rays. The value obtained for reflected β-rays is, therefore, probably too large, and we may take it that this will account for any mistake made in taking emergent γ-radiation proportional to the difference of the readings with lead and cardboard radiators. It may be stated that when no lead was under the active material a similar piece of lead was placed near the active material.

The result obtained does not mean that in a "thin" sheet the slower rays excite only 0·76 of the γ-radiation excited by the faster rays, as we must allow for the greater absorption of the slower β-rays in the lead plate, and also for the fact that the γ-rays formed by the slower rays will be absorbed to a greater extent in the lead.

From equation (3) we get

$$\int_0^d \mathrm{R}\,dx = \frac{1}{\mu}\,\frac{1}{1-\mathrm{P}^2e^{-2\mu d}}(1-e^{-\mu d})(1-\mathrm{P}^2e^{-\mu d}).$$

In the lead sheet (0·1 mm. thick), the various factors in the expression in brackets are nearly equal to unity, so that, owing to the difference in absorption of β-rays, the emergent γ-ray effect will be inversely proportional to the absorption coefficients, *i.e.* we must multiply 0·76 by μ'/μ, where μ' = absorption coefficient of the reflected β-rays in lead.

In an experiment some radium E was placed 6 cm. below an electroscope, and absorption curves were taken with and without a lead reflector under the radium E, the absorption plates being placed just under the electroscope. An analysis of the curves showed that $\mu'/\mu = 1·28$. The radium E was placed 6 cm. below the electroscope, so that β-rays reflected from the absorbing screens could not interfere with the result.

To allow for the greater absorption of the γ-rays in the lead plate, we assume that the average absorption coefficients of γ-rays are proportional to the average absorption coefficients of the β-rays.

It will appear later that in a lead plate 0·1 mm. thick (equivalent to 6·6 foils) 29 per cent. of the emergent γ-rays excited by the direct β-radiation is absorbed (see p. 524). With the assumption we have made, 35 per cent. of the emergent γ-rays excited by reflected β-rays in the lead plate will be absorbed, therefore owing to the greater absorption of the γ-rays we must multiply 0·76 by 71/65, so that in a thin sheet the reflected β-rays excite $0{\cdot}76 \times 1{\cdot}28 \times 71/65$, or 1·06 the γ-radiation excited by an equivalent amount of the direct β-rays, *i.e.*

$$k'/k = 1{\cdot}06 \text{ approx.},$$

since backward β-rays are simply β-rays reflected from the further layers of a plate. The method of finding k'/k takes into account the extra absorption of the softer γ-rays in the wood and aluminium below the electroscope E (fig. 2).

That we should find k' nearly equal to k is not very surprising, as the velocity of the reflected β-rays is not very much less than that of the direct rays. For this reason, we assume that f (p. 517) $= \mu_1/\mu_1'$ where μ_1 and μ_1' are the absorption coefficients in wood of direct and reflected β-rays respectively.

The emergent γ-rays excited by the β-rays in lead have not a definite absorption coefficient, the absorption decreasing as the rays penetrate matter. An average absorption coefficient has, however been obtained. The emergent γ-rays from four lead foils are cut down to 62 per cent. by absorption in lead 0·1 mm. thick; λ is then taken from the equation $e^{-0{\cdot}01\times\lambda} = 0{\cdot}62$ or $\lambda = 47$ in the first tenth of a millimetre. Comparing λ with μ it is found that

$$\mu = 5{\cdot}25\lambda.$$

For incident γ-rays, an average absorption coefficient λ' is taken, such that $\lambda' = 1{\cdot}28\,\lambda$, giving $\mu = 4{\cdot}10\,\lambda'$. We are now in a position to evaluate E and I on the assumptions mentioned. We write

$$\mathrm{E} = k\int_0^d \mathrm{R}e^{-\lambda(d-x)}\,dx, \qquad \mathrm{I} = k \times 1{\cdot}06\int_0^d re^{-\lambda' x}dx,$$

μ, P, λ, and λ' having the values given above.

k is taken so that the emergent γ-radiation from five foils will be 2·20 and the results of the calculations are given in Table IV. For the sake of comparison the experimental values found above, and also numbers calculated as before but with $\lambda = \lambda' = 0$, are given. A comparison with the last numbers shows the extent of absorption in the lead foils. It will be seen that in 0·1 mm. of lead (6·6 foils) about 29 per cent. of the emergent γ-rays is absorbed.

In the calculations, it has been assumed that the velocity distribution o the forward rays is independent of x and d. This is not exactly the case, as the β-rays transmitted through a lead plate are somewhat faster than those originally entering the plate, and there must be a change throughout the thickness of the plate.

It will be seen, however, from Table IV, that the incident γ-radiation from seven foils is absorbed to the extent of only 14 per cent., whereas 33 per cent. of the emergent γ-radiation is absorbed. This shows that most of the γ-radiation is excited in the first layers of a plate, where forward and backward β-rays have nearly the same velocity distribution as direct and reflected β-rays respectively, and equations (3) and (4) hold with accuracy. Further, k varies very little with small changes of velocity, so that if the assumption on which the calculations are based is correct, there should be a very good agreement between experimental and calculated numbers. The Table shows such an agreement, especially for four or more foils. With respect to the other numbers, the agreement is fairly good, as the numbers are more difficult to obtain accurately, and the corrections have a larger effect on the result. The ratio E/I is of the right order for these foils. We have thus very good evidence that the γ-ray is an entity which moves on in very nearly the same direction as the β-ray exciting it. Another way of expressing such a result is to say that the γ-radiation excited by β-rays in a "thin" sheet is invariably emergent.

Table IV.

Radiator.	Experimental values.			Calculated values.			Calculated values (no absorption).	
	Emergent γ-rays = E.	Incident γ-rays.	E/I.	Emergent γ-rays = E.	Incident γ-rays = I.	E/I.	Emergent γ-rays.	Incident γ-rays.
1 lead foil ...	1·05	0·40	2·62	0·92	0·33	2·78	0·96	0·33
2 lead foils ...	1·57	0·80	1·96	1·48	0·78	1·90	1·62	0·80
3 " ...	1·94	1·25	1·58	1·83	1·16	1·57	2·12	1·28
4 " ...	2·17	1·50	1·45	2·08	1·45	1·42	2·52	1·61
5 " ...	2·21	1·67	1·32	2·20	1·65	1·33	2·79	1·90
6 " ...	2·19	1·80	1·22	2·22	1·81	1·22	2·98	2·11
7 " ...	2·17	1·90	1·14	2·20	1·91	1·16	3·26	2·23
9 " ...	1·99	1·94	1·02	2·04	2·01	1·01	3·33	2·41

In Table V, numbers are given which are calculated on the assumption that only 90 per cent. of the γ-radiation, excited by β-rays which strike one side of a thin plate from all possible directions, is emergent. This is done to see if a lower limit can be assigned to the percentage of emergent γ-radiation in such a case.

The numbers are calculated from the equations

$$\mathrm{E} = 0{\cdot}90k\int_0^d \mathrm{R}e^{-\lambda(d-x)}dx + 0{\cdot}10k'\int_0^d re^{-\lambda'(d-x)}dx,$$

$$\mathrm{I} = 0{\cdot}90k'\int_0^d re^{-\lambda' x}dx + 0{\cdot}10k\int_0^d \mathrm{R}e^{-\lambda x}dx,$$

k being again taken so that the emergent γ-radiation from five foils = 2·20.

Table V.

Radiator.	Emergent γ-rays.	Incident γ-rays.	E/I.
1 lead foil	0·89	0·40	2·23
2 lead foils	1·45	0·88	1·65
3 "	1·82	1·30	1·40
4 "	2·08	1·61	1·29
5 "	2·20	1·82	1·21
6 "	2·22	1·95	1·13
7 "	2·20	2·08	1·06
9 "	2·04	2·19	0·93

The ratio E/I (Table V) differs very much from the values given in Table III, especially for a small number of foils. Various errors in our experiments and calculations, however, may account to some extent for the discrepancy between experimental values and those of Table V. As regards the experiments, it is probable that if the ratio E′/I′ (Table III) is too high in some cases, it will be too low in others. In the calculations, the most serious chance of error lies in the value given to k'/k. The value 0·76 found above for the relative emergent γ-radiation excited by reflected β-rays in a lead plate represents the mean of several experiments, which gave results differing by not more than 3 per cent., and is thought not to be too high.

However, if we take the experimental ratio E′/I′ to be 4 per cent. and k'/k 6 per cent. too high, there will then be a rough agreement between experiment and calculation, based on the assumption that 90 per cent. of the γ-radiation in "thin" sheets is emergent. The errors are not likely to be so large and, if we take the lower limit referred to above as 95 per cent., we shall probably leave sufficient margin for error. We therefore conclude that when the β-rays of radium E strike one side of a "thin" plate from all possible directions, between 95 and 100 per cent. of the γ-radiation excited is emergent. Further discussion will be given later.

As backward β-rays are slower than forward β-rays, incident γ-rays should be softer than emergent γ-rays, and this has been proved by another experiment. The electroscope E was replaced by a box, 12·6 cm. cube, from which an electrode passed through a balance chamber to a tilted gold-leaf electroscope. The absorbing materials above the wood W (fig. 2) were a lead plate 0·1 mm. thick and an ebonite plate 1 mm. thick. The results are given below, the emergent γ-radiation from six lead foils being about 70 per cent. of the previous value (Table III).

Table VI.

Radiator LM.	Uncorrected values.		Corrected values.		
	Emergent γ-rays.	Incident γ-rays.	Emergent γ-rays.	Incident γ-rays.	E/I.
Lead (6 foils).........	3·52	2·70	3·50	2·48	1·41
Iron	1·53	0·66	1·53	0·54	2·83

$w = 0·52$.
$f = 0·60$ app.

The corrections, though comparatively uncertain, are small. A comparison of Tables III and VI shows that the incident γ-radiation from a radiator is softer than the emergent γ-radiation.

Taking the emergent γ-radiation from six lead foils as 70 per cent. of the previous value (Table III), the emergent γ-radiation from the iron is 60 per cent. and the wood 35 per cent., showing that the excited emergent γ-radiation is more penetrating the greater the atomic weight.

It has been shown by several experimenters that the β-rays of radium E are not homogenous, but have velocities varying over a fairly wide range. The result obtained would be explained, if in thin sheets of different substances the slower rays produced relatively more γ-rays, the lower the atomic weight of the substance. The γ-rays formed would then be less penetrating the lower the atomic weight. This would indicate that the values of f (p. 517) are not large enough. On the other hand, β-rays of the same speed might excite less penetrating γ-rays in "thin" radiators of low atomic weight.

Taking the sum of emergent and incident γ-radiation (Table IV) for paper, iron, and six lead foils, it is seen that the radiation excited in the paper is 0·61, in the iron 1·70 (no correction for absorption), in the lead 5·00 (correcting for absorption). In the paper, at least 90 per cent. of energy of the β-rays is absorbed, in the iron 60 per cent., in the lead 35 per cent.

For total absorption of the β-rays, we would get γ-rays excited,

In paper = 0·68, In iron = 2·80, In lead = 14·30.

These numbers are roughly proportional to the atomic weight, showing that with the β-rays of radium E, the chance of a β-ray (if it spends its range in a radiator) making a γ-ray is roughly proportional to the atomic weight of the radiator.

Somewhat similar results to those obtained above have been found by Kaye* for the production of X-rays by cathode rays in radiators of the order of 0·00001 cm. in thickness. He found that the emergent X-radiation was greater in amount than the incident radiation, and also more penetrating. An analysis similar to that made above is impossible, but the main explanation of the results must be that the X-radiation tends to move in the same direction as the cathode radiation exciting it.

Theoretical Considerations.

The result that the γ-radiation excited in "thin" sheets is practically all emergent shows that, in general, such radiation, in any amount, is not formed by small deflections of the β-rays. Let us suppose AOB (fig. 5) represents the path of a β-ray suddenly deflected at O, through a right angle, giving rise to γ-radiation. It is clear that such radiation, if due to the acceleration of the particle near O, will not move in any one definite direction, and, even if it did, that direction would probably be OX. Such comparatively small deflections cannot therefore be the cause of the γ-rays, or, at least, of any large amount of such radiation.

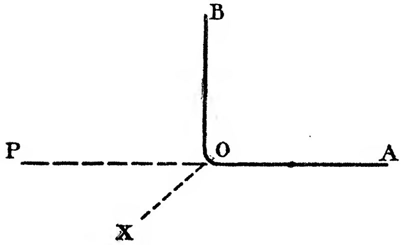

Fig. 5.

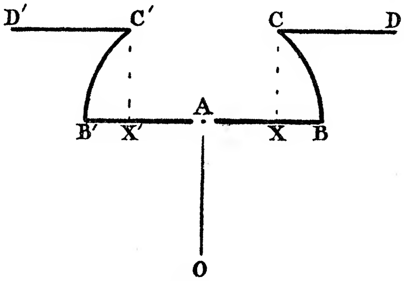

Fig. 6.

It is seen from this that γ-radiation is most likely to be produced when the β-ray is suddenly stopped.† We will, therefore, assume that the γ-ray only arises when the β-ray is suddenly stopped or loses a great part of its energy, and try to explain our results on the theory of Sir J. J. Thomson,‡ which seems, of theories akin to the ordinary pulse theory, the most suitable.

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* 'Camb. Phil. Soc. Proc.,' November, 1909, vol. 15, p. 269.

† It is considered that the β-ray stops if it forms a γ-ray in the way supposed by Bragg, as well as by loss of speed.

‡ 'Phil. Mag.,' February, 1910, vol. 19, p. 301.

In this theory, the electron has its electric field concentrated in a double cone, the vertex of which is at the centre of the electron. Let us suppose that such an electron, a β-ray of radium E moving in the direction OA, is suddenly stopped at A (fig. 6). AB represents the part of the tube at rest, CD that part moving with the original velocity, which, in the case of the β-ray of radium E, is, on an average, 0·8 that of light. The electric and magnetic forces in the kinks BC, B′C′, constitute the γ-radiation. As $CX = 0{\cdot}8\ AC$, the angle XAC is nearly 53°, and, whatever the density of energy in the kink, such radiation will not explain our results. Assuming that the energy of the kink is concentrated at C and C′, and allowing for the possible directions of the tube AB, the radiation will, on an average, move out in a circle along a cone, of which OA is axis and OC generator. It can be calculated that with such an arrangement only 82 per cent. of the γ-radiation excited by β-rays in a "thin" sheet will be emergent, the β-rays striking the sheet from all possible directions. The theory, therefore, cannot account for the production of excited γ-rays.

It seems to the writer that the assumption that the ray is an entity is correct, although the experiments do not altogether exclude the view that γ-radiation is a disturbance which spreads out as it travels along. If such were the case, however, the disturbance would, on an average, have to be confined to a cone of small solid angle, the axis of which would be the direction of motion of the exciting β-ray. With such a disturbance we have the old difficulty of accounting for the fact that the properties of X- and γ-rays do not vary apparently with the distance from their source.

On the view that the excited γ-ray is an entity there are two distinct theories—

(1) The β-ray forms part of the γ-ray and gives it its energy and direction—Bragg's theory.*

(2) The β-ray supplies the energy, but does not form part of the γ-ray, which travels on as a "bundle" of energy, without change of form. Stark† has put forward a theory of this kind. He considers the X- or γ-ray to be of the same nature as light, and obtains the direction of the radiation by considerations of momentum.

Summary.

The results of the experiments are summarised below :—

(1) The emergent γ-radiation excited by β-rays in different radiators is generally greater in amount and more penetrating than the incident radiation. It increases in penetrating power with the atomic weight of the radiator.

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* 'Phil. Mag.,' October, 1907, vol. 14, p. 429, and September, 1910, vol. 20, p. 385.

† 'Phys. Zeitschr.,' 1909, 1910.

(2) The ratio of emergent to incident γ-radiation is greater, for radiators of the same material, the thinner the radiator, for radiators of different materials thick enough to stop the β-rays, the lower the atomic weight.

(3) Results obtained point to the conclusion that the ray is an entity, the direction of which is nearly that of the β-ray exciting it.

(4) For β-rays of the speed used, the chance of a β-ray making a γ-ray is roughly proportional to the atomic weight of the radiator, provided the β-ray spends its range in the radiator.

In conclusion, the writer has much pleasure in expressing his best thanks to Prof. Rutherford for his very helpful interest in this research, and for the use of the very active preparation of radium D necessary.

The After-luminosity of Electric Discharge in Hydrogen, observed by Hertz.

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In previous papers I have examined certain striking cases of after-luminosity in gases through which the electric discharge has been passed. The cases dealt with fall under two heads, those due to ozone, and those due to active nitrogen. I wish now to pass to a case in which neither of these substances is concerned.

Hertz* described a phenomenon of after-luminosity which he had observed in hydrogen. The method of investigation was somewhat special. A series of jar discharges was passed through a small discharge tube, with an open end, arranged inside a bell jar. It was then observed that at each discharge a stream of luminous gas was squirted from the end of the small discharge tube into the bell jar. This is apparently due to a kind of explosive action of the spark—the same, probably, as that described by De La Rue and Muller.† The method is well adapted to show the afterglow in other gases, nitrogen or air, for instance, but the immediate concern is with hydrogen. With this gas, Hertz sometimes observed a jet of blue luminosity, which was best developed at a pressure of

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* 'Wied. Ann.,' 1883, vol. 19, p. 78.

† 'Phil. Trans.,' 1880, vol. 171, p. 86.